Tunable electro-optic wavelength filter based on lossy-guided mode resonances

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Abstract: In this work an optical fiber tunable filter based on lossy guided-mode resonances (LGMR) is proposed. It consists of a multilayer structure deposited onto the surface of a plastic cladding removed multimode fiber. The first layer is used to generate the LGMR and to work as the first electrode as well; the second one to tune the filter and the outer layer forms the other electrode. The fabricated filter has demonstrated a good sensitivity to the applied voltage showing a change of the LGMR wavelength of 0.4 nm/V. Among other applications, this filter is intended to be used as electro-optic wavelength filter or modulator.

OCIS codes: (310.0310) Thin films; (250.0250) Optoelectronics; (260.5740) Resonance.

References and links

1. A. A. Abramov, A. Hale, R. S. Windeler, and T. A. Strasser, "Temperature sensitive long period fiber gratings for wideband tunable filters," in *Optical Fiber Communication Conference*, San Diego, California, Feb. 21–26, 1999.
2. D. Costantini, H. G. Limberger, R. P. Salathe, C. A. P. Muller, and S. A. Vasiliev, "Tunable loss filter based on metal coated long period grating," in *Proc. ECOC'98*, Madrid, Spain, Sept. 1998, pp. 391–392.
3. S. Hyun Nam, J. Lee, and S. Yin, "Control of resonant peak depths of tunable long-period fiber gratings using overcoupling," Opt. Commun. **284**(4), 961–964 (2011).
4. Q. Chen, J. Lee, M. Lin, Y. Wang, S. S. Yin, Q. Zhang, and K. M. Reichard, "Investigation of tuning characteristics of electrically tunable long-period gratings with a precise four-layer model," J. Lightwave Technol. **24**(7), 2954–2962 (2006).
5. L. Sireto, G. Coppola, G. Abatte, G. C. Righini, and J. M. Otón, "Electro-optical switch and continuously tunable filter based on a Bragg grating in a planar waveguide with liquid crystal overlayer," Opt. Eng. **41**(11), 2890–2893 (2002).
6. F. J. Arregui, I. R. Matias, K. L. Cooper, and R. O. Claus, "Fabrication of microgratings on the ends of standard optical fibers by the electrostatic self-assembly monolayer process," Opt. Lett. **26**(3), 131–133 (2001).
7. F. Yang and J. R. Sambles, "Determination of the optical permittivity and thickness of absorbing films using long range modes," J. Mod. Opt. **44**(6), 1155–1163 (1997).
8. M. Marciniak, J. Grzegorzewski, and M. Szustakowski, "Analysis of lossy mode cut-off conditions in planar waveguides with semiconductor guiding layer," IEEE Proc. J. **140**(4), 247–251 (1993).
9. I. Del Villar, C. R. Zamarreño, M. Hernaez, I. R. Matias, and F. J. Arregui, "Generation of lossy mode resonances with absorbing thin-films," J. Lightwave Technol. **28**, 3351–3357 (2010).
10. I. Del Villar, I. R. Matias, F. J. Arregui, and R. O. Claus, "Analysis of one-dimensional photonic band gap structures with a liquid crystal defect towards development of fiber-optic tunable wavelength filters," Opt. Express **11**(5), 430–436 (2003).
11. C. R. Zamarreño, M. Hernaez, I. Del Villar, I. R. Matias, and F. J. Arregui, "ITO coated optical fiber refractometers based on resonances in the infrared region," IEEE Sens. J. **10**(2), 365–366 (2010).
12. M. Hernáez, I. Del Villar, C. R. Zamarreño, F. J. Arregui, and I. R. Matias, "Optical fiber refractometers based on lossy mode resonances supported by TiO2 coatings," Appl. Opt. **49**(20), 3980–3985 (2010).
13. I. Del Villar, C. R. Zamarreño, P. Sanchez, M. Hernaez, C. F. Valdivielso, F. J. Arregui, and I. R. Matias, "Generation of lossy mode resonances by deposition of high-refractive-index coatings on uncladded multimode optical fibers," J. Opt. **12**(9), 095503 (2010).
14. I. Del Villar, C. R. Zamarreño, M. Hernaez, I. R. Matias, and F. J. Arregui, "Lossy mode resonance generation with indium tin oxide coated optical fibers for sensing applications," J. Lightwave Technol. **28**(1), 111–117 (2010).
15. R. C. Jorgenson and S. S. Yee, "A fiber-optic chemical sensor based on surface plasmon resonance," Sens. Actuators B **12**(3), 213–220 (1993).
16. C. R. Zamarreño, S. Lopez, M. Hernaez, I. Del Villar, I. R. Matias, and F. J. Arregui, "Resonance-based refractometric response of cladding-removed optical fibers with sputtered indium tin oxide coatings," Sens. Actuators B **175**, 106–110 (2012).

#195448 - $15.00 USD Received 8 Aug 2013; revised 26 Sep 2013; accepted 4 Nov 2013; published 13 Dec 2013

17. C. R. Zamarreño, M. Hernáez, I. Del Villar, I. R. Matias, and F. J. Arregui, "Optical fiber pH sensor based on lossy-mode resonances by means of thin polymeric coatings," Sens. Actuators B **155**(1), 290–297 (2011).
18. J. M. Corres, F. J. Arregui, and I. R. Matias, "Sensitivity optimization of tapered optical fiber humidity sensors by means of tuning the thickness of nanostructured sensitive coatings," Sens. Actuators B **122**(2), 442–449 (2007).
19. Q. Chen, M. R. Lin, J. E. Lee, Q. M. Zhang, and S. Yin, "Nanocomposites with very large electro-optic effect and widely tunable refractive index," Appl. Phys. Lett. **89**(14), 141121 (2006).
20. C. R. Zamarreño, I. Del Villar, M. Hernáez, I. R. Matias, and F. J. Arregui, "Optical fiber refractometers with tunable sensitivity based on ITO coatings," Sens. Lett. **8**(5), 744–746 (2010).
21. C. R. Zamarreño, M. Hernáez, I. Del Villar, I. R. Matias, and F. J. Arregui, "ITO coated optical fiber refractometers based on resonances in the infra-red region," IEEE Sens. J. **10**(2), 365–366 (2010).
22. C. R. Zamarreño, M. Hernáez, I. Del Villar, I. R. Matias, and F. J. Arregui, "Tunable humidity sensor based on ITO-coated optical fiber," Sens. Actuators B **146**(1), 414–417 (2010).
23. R. Su, G. Zhong, Q. Fu, L. Zhang, H. Fong, and L. Zhu, "Polarity-induced ferroelectric crystalline phase in electrospun fibers of poly(vinylidene fluoride)/polyacrylonitrile blends," J. Mater. Res. **27**(10), 1389–1398 (2012).
24. D. Y. Jeong, Y. K. Wang, M. Huang, Q. M. Zhang, G. J. Kavarnos, and F. Bauer, "Electro-optical response of the ferroelectric relaxor poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) terpolymer," J. Appl. Phys. **96**(1), 316–319 (2004).
25. A. Glück, W. Halder, G. Lindner, H. Müller, and P. Weindler, "PVDF- excited resonance sensors for gas flow and humidity measurements," Sens. Actuators B **19**(1–3), 554–557 (1994).
26. H. Zhen, G. Li, K. Zhou, and X. Liu, "Tunable Fabry-Perot interferometer from ferroelectric polymer based on surface energy modification," Opt. Express **18**(15), 15784–15789 (2010).
27. J. M. Corres, Y. R. Garcia, F. J. Arregui, and I. R. Matias, "Optical fiber humidity sensors using PVdF electrospun nanowebs," IEEE Sens. J. **11**(10), 2383–2387 (2011).
28. J. R. Kim, S. W. Choi, S. M. Jo, W. S. Lee, and B. C. Kim, "Electrospun PVdF based fibrous polymer electrolytes for lithium ion polymer batteries," Electrochim. Acta **50**(1), 69–75 (2004).
29. S. López, I. del Villar, C. Ruiz Zamarreño, M. Hernaez, F. J. Arregui, and I. R. Matias, "Optical fiber refractometers based on indium tin oxide coatings fabricated by sputtering," Opt. Lett. **37**(1), 28–30 (2012).

1. Introduction

The use of materials with variable thermal or electro-optic properties allows the fabrication of tunable photonic devices. Among these devices, electrically tunable filters based on electro-optic materials have great interest because of their fast tuning speed and their easy control. Wideband tunable filters are used in optical communications because they offer active control in optical network, for example to enhance the performance of gain flattening filters [1,2].

These filters could be classified into intrinsics and extrinsics. Most of the intrinsic tunable filters published were based on fiber Brag grattings, micrograttings, long period gratings or photonic crystal fibers, among others [3–7]. In this work, an intrinsic electro optic tunable filter will be presented based on an overlay deposited onto a plastic cladding removed optical fiber.

As it has been reported in previous works, thin-film overlays fabricated onto the core of optical fibers can produce selective optical power absorption at certain wavelengths, also known as resonances. Different types of resonances can be described attending to the dielectric properties of the outer thin-film surrounding the optical waveguide. Surface Plasmon Resonances (SPRs) can be obtained when the material meets some specific criteria: the real part of the thin-film permittivity must be negative and higher in magnitude than both its own imaginary part and the real part of the permittivity of the material surrounding the thin-film (i.e. the optical waveguide and the surrounding medium in contact with the thin-film) [6].

There exists other type of resonances which are caused by coupling to a specific type of guided mode: a lossy guided mode. Some authors consider these modes as long-range guided modes [7], whereas others call them lossy modes [8,9]. Even though in previous works the nomenclature we have used to mention the phenomenon was lossy mode, we consider now that the term lossy guided-mode could be more convenient because in this way we include both notations. Lossy guided-mode resonances occur when the real part of the thin-film permittivity is positive and higher in magnitude than its own imaginary part as well as the real part of the permittivities of both the optical waveguide and the external medium surrounding the thin-film [7,8]. As a rule of design, the material used for these purposes should have a high refractive index real part and not null imaginary part as it has been demonstrated

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experimentally by adding ITO [10], TiO_2 [11] or In_2O_3 [12] coatings. In contrast to SPRs, LGMRs enable the generation of multiple resonances without modifying the optical fiber geometry and can be obtained with both TE and TM polarized light [9,13–15]. Furthermore, LGMR extend the available range of materials susceptible of being used in the overlays from metals or semiconductors in the case of SPR, to also polymers and metal oxides, in the case of LGMR [16–18].

Much effort has been done to enhance the wavelength range over which the filter can be tuned by using materials with large electro-optic coefficient [19]. LiNbO3 is one of the most widely used materials and has a change of 0.1% of the refractive index. Using copolymers, terpolymers and nanocomposites a higher change of the refractive index has been obtained (0.4%) and a wavelength change of up to 50nm [19].

In order to increase the tuning range of tunable filters, a different approach has been followed in this work. Instead of using high electro-optic specially designed materials it has been used a widely available polymer (PVdF) and a high sensitive optical structure (LMRs), which in contrast to LPGs, are obtained at the same time that the internal electrode is deposited, what greatly reduces the cost of the device. In particular, this work analyze the fabrication of a tunable fiber optic filter using a nanometric multilayer structure in an overlay deposited onto the core of a plastic cladding removed multimode optical fiber (PCRMOF). The high sensitivity of LMRs allows obtaining a wavelength change of up to 70nm using PVdF, which refractive index change is about 0.1%. To our knowledge, this is the first time that a tunable EO filter based on LGMRs is presented in the literature.

This device presents some advantages with regard to previous electro optic tunable filters: it requires a simple set up for operation, besides it is able to work with halogen withe light sources and it does not need delay fibers or high-dispersion fibers. This device also offers a larger displacement than LPGs even when PVdF co-polymers are used in the LPGs devices. Finally, the fabrication of the device is simple and repeatable, although small variations in the thickness of the different layers may occur, it only will lead to small variations in the initial wavelength or the operating voltage.

The manuscript is organized as follows: firstly, in section II, the structure of the tunable wavelength filter is analyzed. Then, the fabrication of the device and the experimental set-up is described in section III. In section IV the filter performance is discussed, and finally some concluding remarks are exposed in Section V.

2. Structure of the tunable wavelength filter

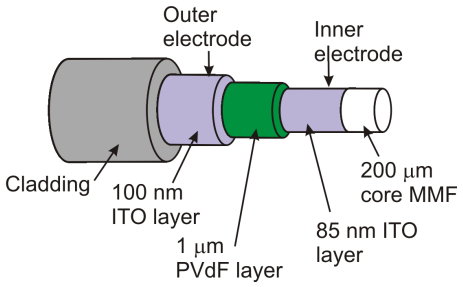

Fig. 1. Scheme of the multilayer structure of the EO tunable wavelength filter.

The structure of the wavelength filter is represented in Fig. 1. The multilayer structure deposited onto a 5 cm. long plastic cladding removed 200 μm core optical fiber is formed by a first layer of Indium Titanium Oxide (ITO), over which another overlay of polyvinylidene difluoride (PVdF) is deposited. This multilayer overlay is topped with a second layer of ITO. In the first ITO coating, the LGMR is generated. More details of this physical phenomenon can be found in the literature [12, 20–22].

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Regarding the second layer, in previous works it has been reported a very large electro optic effect induced by reversible molecular chain conformation change in relaxor ferroelectric terpolymers PVdF co-polymers [19,23,24]. Films free from mechanical constraints exhibit refractive index change of $\Delta n/n = -2.6\%$ under 80 V/μm [19]. Furthermore, PVdF has been already employed for the development of sensitive film sensors and interferometers [25,26]. Particularly, electrospun PVdF has been used for the fabrication of polymer batteries, amperometric biosensors and humidity sensors [27,28]. In this work it will be used to tune the wavelength of the LGMR, generated in the first ITO layer, just by applying a voltage. So, ITO was used to generate LGMRs in the visible-infrared spectral region, and taking advantage of its conductivity, it will be also used as an inner electrode to apply voltage to the PVdF coating in order to change the refractive index of this PVdF overlay which provokes the shift of the LGMR spectral response.

In other words, the structure obtained when this PVdF nanoweb based overlay is deposited onto the ITO coating, permits to change its refractive index as a function of the applied voltage obtaining a high sensitivity.

Finally, an additional external layer of 85 nm of ITO was deposited in order to work as an external electrode. See top of Fig. 2 for more details.

3. Experimental details

In this section both the coating fabrication and characterization setup are presented.

3.1.Coating fabrication

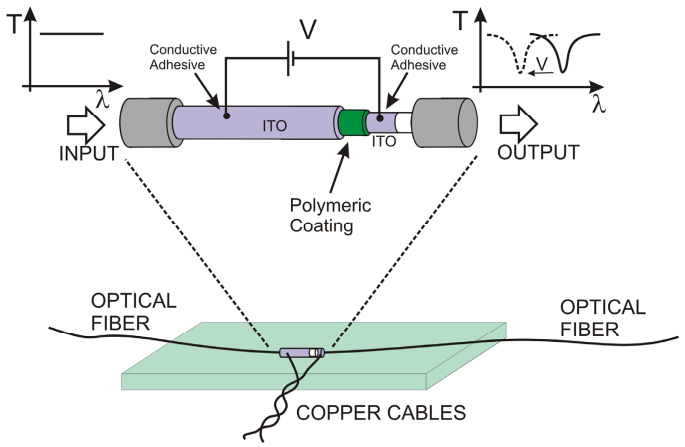

Fig. 2. Detail of the device.

Plastic-clad silica fibers of 200/225 μm core/cladding diameters respectively, purchased from Thorlabs Inc were used. Prior to the coating process, a 5 cm. long portion of this fiber cladding was chemically removed in order to expose the optical fiber core. To prevent the removed cladding optical fiber from undesired breakages, it is attached to a holder as shown in Fig. 2.

Prior to the deposition of the first ITO coating, it is necessary to prepare the optical fiber following a procedure which basically involves the removal of the optical fiber cladding along a length of 10 cm followed by several sonication cleaning processes. For the deposition of the ITO coatings, sputtering equipment (K675XD from Quorum Technologies, Ltd.) was used with a partial pressure of Argon between $6 \times 10–3$ and $9 \times 10–3$ mbar and an intensity of 150mA. The target used had a In:Sn ratio of 90:10. Since the sputtering technique is mainly intended to be used with planar substrates, it was necessary to implement a new mechanism in order to rotate the optical fiber during the deposition at constant speed. More

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details of this fabrication procedure can be found in [29]. This first ITO layer of thickness of 85 nm is where the LGMR is generated and also forms the inner electrode necessary to apply the voltage to the final device.

Then, the resultant device with this first overlay of ITO, was coated with PVdF by means of the electro-spinning deposition technique. This technique has been used in other works with the same material and it allows achieving thin PVdF films [27,28]. PVdF was dissolved in N, N-Dimethylformamide (DMF) and acetone at 5% wt (from Sigma Aldrich) and this dissolution is preheated at 60°C prior to the electro-spinning process. The total amount of PVdF necessary was lower than 100 µl. For this coating it was used an electrospinning machine (ND-ES) (from Nadetech, Ltd.). This electrospun nanoweb based overlay consists of a continuous polymeric fiber in the range of nanometers obtained by means of a high voltage field and deposited onto the substrate, in this case the first ITO layer. When a high voltage (18 kV, 20 cm and 10 µl/min) is applied to the polymeric dissolution, it becomes charged, and due to electrostatic repulsion a stream of liquid erupts from the surface and is launched towards the grounded electrode. More details of this technique can be found in [27]. When the molecular cohesion of the dissolution is sufficiently high, the polymeric fiber is formed and elongated due to repulsion forces, evaporating the solvent during the trajectory until it is finally deposited onto the collector. The thinning of the fibre leads to the fabrication of nanofibers that superpose randomly forming a fiber nanoweb. In order to achieve a homogeneous coating, this process can be improved attaching the optical fiber to a rotating mechanism placed into the electro-spinning deposition place, similar to the one used in the sputter coating deposition technique. Then, the polymeric fiber was spun at constant speed (500 rpm) during the deposition. PVdF overlay had a thickness of 1 µm.

The external layer of 100 nm of ITO was deposited following the same procedure used in the first overlay. ITO coatings revealed a homogeneous coverage of the optical fiber core surface. In Fig. 3(a) the SEM image of the cross section of the fiber with the first ITO overlay is shown. The PVdF fiber nanoweb overlay deposited by electro-spinning is shown in Fig. 3(b) and the surface view of this same coating is shown in Fig. 3(c). With regard to repeatability in the fabrication process, it must be taken into account that electro-spinning process has always a random component and that it becomes difficult to achieve a given thickness with precision so that there will be small differences in the operating voltage that should be applied.

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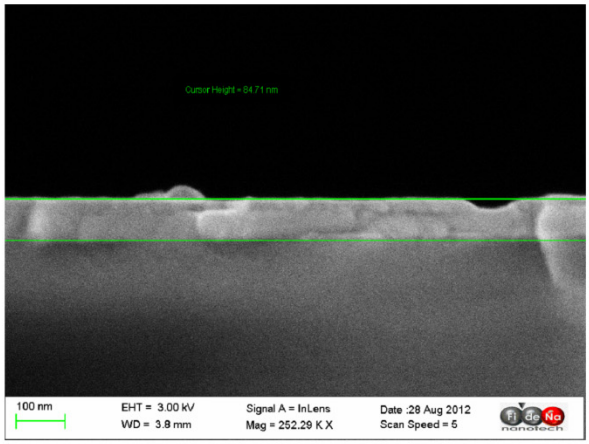
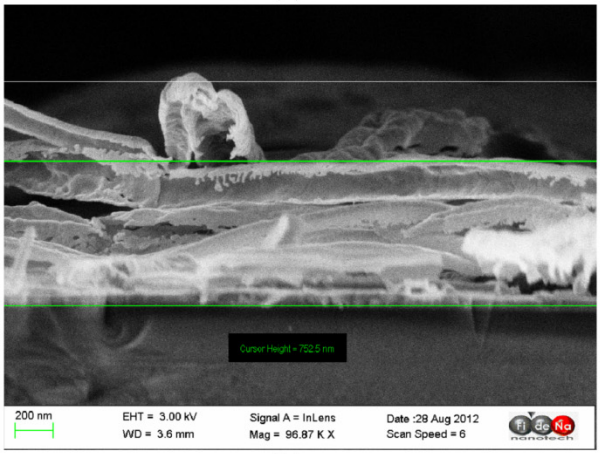
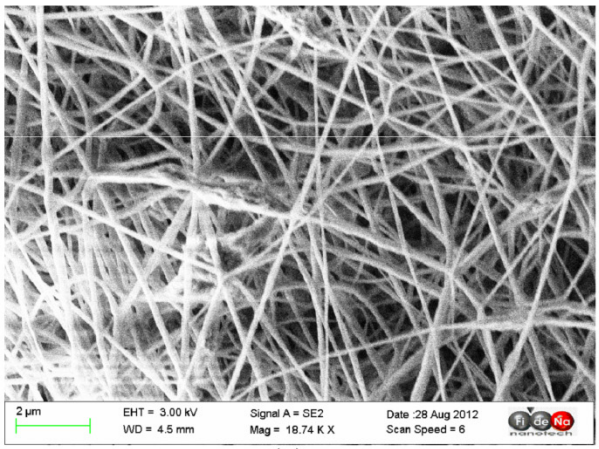


(a)



(b)



(c)

Fig. 3. SEM image of the cross section of the fiber a) ITO coating b) PVdF nanoweb coating by electro-spinning technique and c) surface view of the PVdF nanoweb coating.

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3.2. Characterization setup

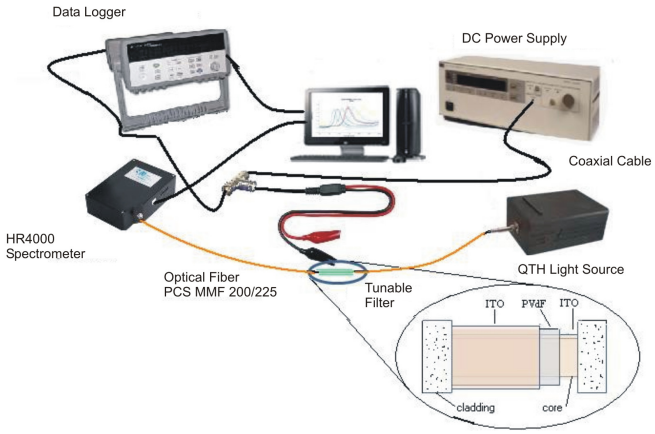

Fig. 4. Experimental setup.

Once the multilayer gets deposited onto the fiber, an approximately 5 cm portion of the coated fiber core was cleaved (LCD-200 Vytran, Inc.) and spliced (FITEL S176, Furukawa Co., Ltd.) on both ends to 200 μm core diameter optical fiber pigtails. One of the ends was connected to a white light source (QTH light source from AlphaBright) and the other one to a visible-IR spectrometer (HR4000 from Oceanoptics, Inc.) in a typical transmission setup, as shown in Fig. 4. Thus, the light coupled into the optical fiber passes through the cladding removed region located in the optical transmission path. A DC voltage supply (Agilent-HP 6015A) was used to apply an external voltage to the sensitive region and a data acquisition device (Agilent 34970A) was employed to collect voltage data at the same time as spectra were being collected in the spectrometer. Several cycles were done in order to ensure repeatability and reversibility.

4. Results

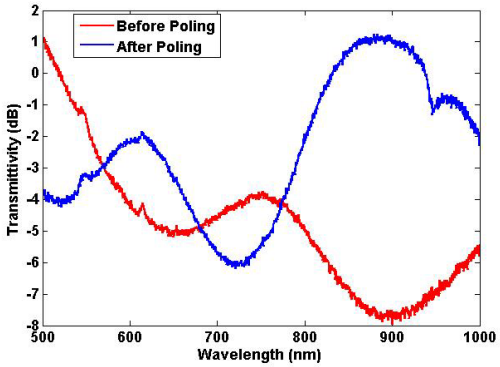

Fig. 5. Transmittance spectra of the device before and after poling.

In the next paragraphs, it will be shown that PVdF coatings can spectrally shift the LGMRs produced by the first ITO nanofilm with the application of an external voltage. Prior to any measurements, it is necessary to apply an electrical poling to the multilayer structure, particularly to the PDdF nanoweb overlay, in order to obtain a significant piezoelectric response. This poling process usually involves heating and mechanical stretching plus the application of an electric field, but for the thin films used in this structure, the application of an electric field is quite enough. Piezoelectricity can be obtained by orienting the molecular

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dipoles of polar polymers such as PVDF in the same direction by subjecting appropriate films to an intense electric field: this is polarization. This polarization is mainly attributable to the spatial arrangement of the segments of the macromolecular chains. The polarized material is thermodynamically stable up to about 90°C.

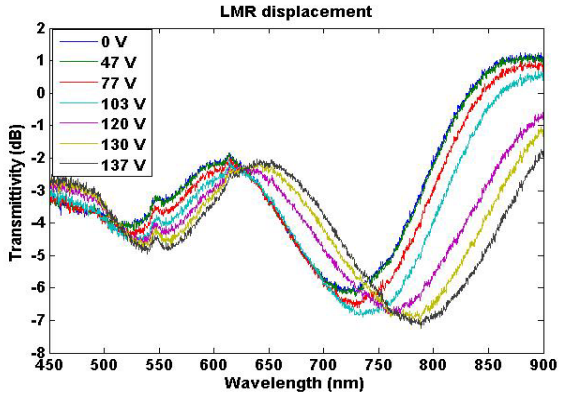

Fig. 6. LGMR peak shift produced by external voltage.

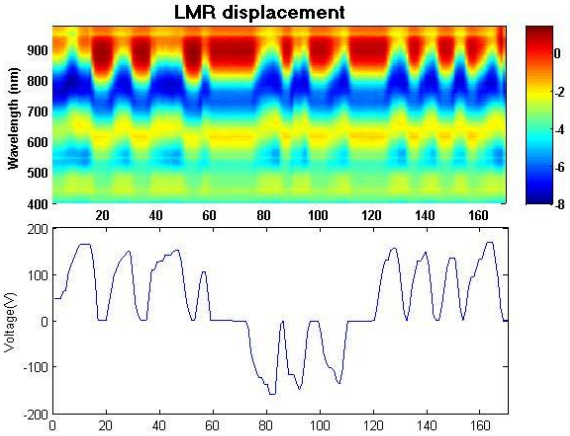

Fig. 7. Some cycles of both polarity voltages, Fig. on the bottom shows the voltage applied to the device and Fig. on top plots the spectral response of the device under this voltage.

The effect of the poling process over the LGMR is shown in Fig. 5. It can be observed a noticeable blue-shift of the device transmittance spectra when the poling process is applied. Before poling, the first resonance is located at 900 nm. Besides, the device shows a second LGMR in the region of 650 nm. After the poling process, the first resonance moves to 720 nm, meanwhile the second one shifts to 515 nm. This change in the LGMR wavelength is due to a permanent change in the orientation of the PVdF molecules, that involves a change in the refractive index of the material. Although this change is always towards lower wavelengths, the final displacement is not completely predictable.

Once the device has been poled, it is ready to be used. So by the application of an external voltage, the transmittance spectra changes and it is collected by the spectrometer. Figure 6 shows the LGMR peaks shift to longer wavelengths, due to the changes in the refractive index of the PVdF coating, when an external voltage is applied. The device requires the application of higher voltages than the voltage used in the poling stage for its operation. It is obtained a shift of 70 nm and 23 nm, corresponding to the first and second LGMR, respectively. Figure 7 shows the response of the device to some cycles of both polarities voltage.

The response of this device is symmetrical with regard to voltage polarity. The peak of the LGMR is always shifted to longer wavelengths, although the behavior is not the same

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because the slope of the LGMR is affected by polarity. Also, it can be seen that the peak corresponding to the first LGMR is the one which has the greatest wavelength shift. Hysteresis reaches more importance when voltage boundaries are exceeded, which are different for each polarity. All the experimental results were obtained at room temperature (25°C).

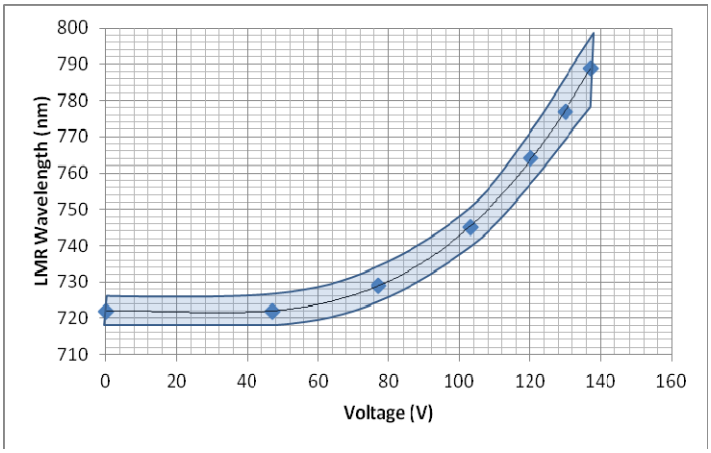

Fig. 8. Response of the device to voltage variations (corresponding to the first resonance). Shadowed the range of variation when subjected to 50 voltage cycles.

In Fig. 8, it can be seen the response of the filter, corresponding to the first resonance to voltage variations. A sensitivity of 0.40 nm/V is obtained for the first LGMR with a response time of 40 ms, as can be inferred from Fig. 9. This sensitivity applies for the range 0 to 137 volts, although the displacement of the LGMR wavelength only occurs for voltages greater than 50 volts. The slope of the graphic is over 1 nm/V for voltages greater than 80 volts.

The filter has a 125 nm bandwidth and a q factor of 5.8. This characteristics could be improved using other optic fiber structures like tapered SM fiber or D-shape SM fibers. Although LGMRs have demonstrated to have greater sensitivity than other all-in-fiber devices, the sensitivity of the filter can be improved using PVdF co-polymers. This will be performed in subsequent experiments as well as the development of new coating methods in order to improve thickness control and electric isolation.

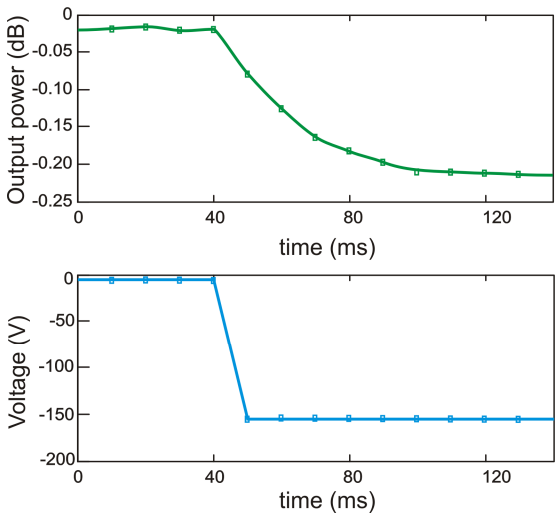

Fig. 9. Response time of the LGMR tunable filter.

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The use for the first time of the LGMR phenomenon to fabricate tunable electro optic wavelength filters indicates that the structure studied in this work should become an interesting platform for the design of future photonic devices, not only filters. In any case, further discussions about the filter characteristics towards a final application have to be implemented and will be published elsewhere.

The main objective of this work has been to demonstrate the feasibility to change the LGMR resonances using an electro-optic overlay. Taking into account the time response, range of variation and resonance bandwidth this device can be applied for the active control of optical networks and for sensing, for example as transducer of electrical signals in power distribution networks.

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